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In the course of a theoretical study of optimizing the redistribution of charged particle longitudinal energy into the transverse component, a law for the variation of the magnetic field in a magnetic trap was derived. A variable field magnetic trap is described. Up to 70% redistribution was obtained for electrons.

A previous paper (Ref. 1) has shown that a charged particle moving in a /410* stationary spatially periodic magnetic field effectively interacts with it and redistributes almost half the injection energy from the longitudinal into the transverse component. This effect was observed when the conditions of its distinctive "resonance" $\omega_H = \frac{2\pi}{L} v_{||}$ were fulfilled. The entire energy of the charged particles in the stationary magnetic field is maintained; therefore, an increase in energy of transverse motion is accompanied by reduction of energy of longitudinal motion. As $v_{||}$ decreases, the "resonance" conditions are disturbed and the particles leave the state of "resonance".

For more effective redistribution of longitudinal motion energy into the transverse component, the particle must be maintained in "resonance" for a longer period. This may be done in two ways (Ref. 2): (1) by decreasing period L of the modulating magnetic field while keeping the main field constant; (2) by reducing the main magnetic field H_z along the trap axis while keeping /411 the modulation period constant.

We have investigated the second method. To derive a law of change in the fundamental magnetic field, for which the condition of precise "resonance" $\omega_H = \frac{2\pi}{L} v_{||}$ over the whole length of the spatially periodic magnetic field would be fulfilled, we made a theoretical study of charged particle motion in a magnetic field of the type

$$H_z = H_{0z}[1 + hl_0(\nu, r)\cos \nu z] \tag{1}$$

under the following assumptions: $\nu = \frac{2\pi}{L} = \text{const}$, $h = \frac{H\sim}{H_z} = \text{const}$, and $\omega_H = \frac{2\pi}{L} v_{||}$ over the whole length of the spatially periodic magnetic field; h is the coefficient of modulation of the spatially periodic magnetic field.

The equation of motion is written in the form

$$\ddot{r} + \frac{\omega_H^2}{4}[1 + 2hl_0(\nu, r)\cos \nu z]r = 0. \tag{2}$$

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* Numbers in the margin indicate pagination in the original foreign text.

By change of variables, this equation was reduced to the canonical form of the Mathieu equation, which was solved by an asymptotic method. Solution of the equation of motion resulted in a law of change in the main magnetic field H_z over the whole length of the spatially periodic magnetic field, for which the condition of exact "resonance" $\omega_H = \frac{2\pi}{L} v_{\parallel}$ is fulfilled over the whole length of the system:

$$H_z = \frac{mcv_0\nu}{e}\left\{1 - [1 + (r_0\nu)^{-2}]e^{\frac{h\nu z}{2}}\right\}^{\frac{1}{2}}, \qquad (3)$$

where r_0 is the input radius for the particle into the spatially periodic magnetic field. From parametric resonance theory, it is known that with low coefficients of parameter modulation, a narrow resonance curve is obtained. To obtain a noticeable interaction between charged particle and spatially periodic magnetic field with a low modulation coefficient (h = 5%), a spatially periodic magnetic field with a great number of periods was created.

Description of Apparatus

Figure 1 shows (b) a diagram of the device and (a) magnetic field distribution along the axis of the trap. The vacuum chamber is a tube 0.1 m in diameter and about 4 m long. It was evacuated at both ends with oil-vapor pumps to a pressure of $1.33 \cdot 10^{-4}$ N/m^2. The length of the solenoid creating the main magnetic field was 3 m. This field, in accordance with formula (3), varied along the trap axis from $9.3 \cdot 10^3$ to $4.8 \cdot 10^3$ amp-turns per meter. A system of coils connected in a direction opposite to each other produced the spatially periodic modulation of the main magnetic field. This coil system was arranged inside the solenoid producing the main field. Modulating magnetic field strength varied in accordance with formula (3), creating a constant modulation factor of 5% over the whole length of the spatially periodic magnetic field. The number of periods formed in the spatially periodic magnetic field was 19.5. Electron injection was by electron gun with a directly heated cathode situated outside the magnetic field. Deflecting plates were employed to extract the beam for the desired r_0. Electron injection energy was 1250 eV ($2 \cdot 10^{-16}$ joule).

/412

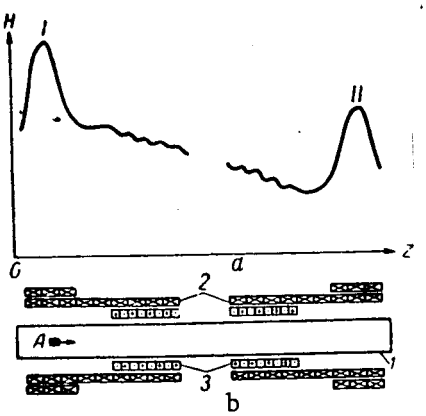

Figure 1

Diagram of Apparatus and Distribution of Magnetic Field Along Trap Axis:

I and II -- first and second magnetic "mirrors"; 1 -- vacuum chamber; 2 -- main magnetic field coils; 3 -- modulating magnetic field coils; 4 -- electron gun.

In the first part of the work, we solved the problem of creating a main magnetic field varying over the length, in conformity with formula (3). The necessary law of magnetic field variation along the axis was effected by having a certain law of current variation in every magnetic coil by connecting the proper resistance to every coil (Figure 2). A frequency-doubling magneto-modulation pickup (Ref. 4, 5) and an EPP-09 automatic recorder were used to measure the magnetic field. The pickup was moved by an electric motor along the axis of the magnetic system at a rate of 0.007 m/sec. Figure 3 gives the electrical block diagram of the pickup. The pickup cores were made of E-310 steel. Pickup size was 0.01 x 0.01 x 0.008 meter. The pickup was calibrated in the field of the long solenoid. The diagrams obtained on the EPP-09 were processed with a calibration curve (Figure 4). Selection of frequency and current amplitude of superposed magnetization gave the optimum pickup operating conditions, and the instrument made it possible to measure magnetic field gradients of ~5% with an accuracy of 1.5%.

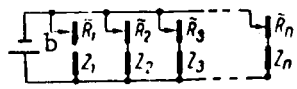

Figure 2

Wiring Diagram of Main Magnetic Field Coils.

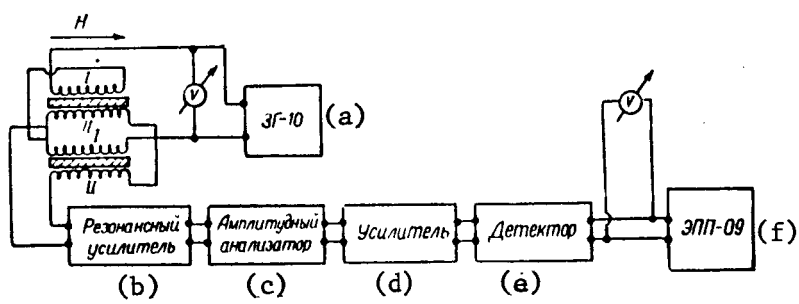

Figure 3

Electrical Block-Diagram of Magnetic Field Measuring Device / 413

(a) - ZG-10 acoustic wave generator; (b) - Resonance amplifier;
(c) - Amplitude analyzer; (d) - Amplifier; (e) - Detector;
(f) - EPP-09 self-recorder

Figure 5 gives the distribution of magnetic fields along the trap axis. The top curve is the change in modulating field $H_{\sim}$ along the axis; the lower curve is the distribution of the main magnetic field H_z. It is evident from the figure that the main magnetic field coincides to within 2% with the magnetic field computed by formula (3). By placing a segment of the spatially periodic magnetic field between the magnetic mirrors, we formed the magnetic trap. The magnetic field in the "mirrors" is small.

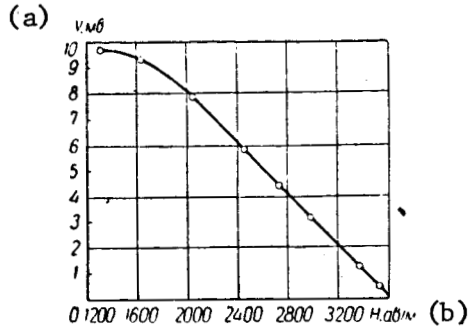

Figure 4

Dependence of Voltage V of Magnetic Pickup Second Harmonic on Magnetic Field H.

(a) - V,mv; (b) - H, amp-turns per meter.

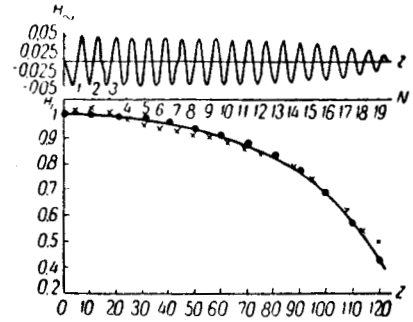

Figure 5

Distribution of Magnetic Fields Along Trap Axis:

N -- Period number of modulating magnetic field;
••• -- Magnetic field calculated from formula (3);
××× -- Magnetic field created in trap.

Results of Experiment

A phosphor-covered screen was used to study charged particle motion through the spatially periodic magnetic field. The error by this method is great (up to 10%); nevertheless, it made it possible to obtain a number of interesting results. Because of the spatially periodic magnetic field effect, /414 the charged particles moved along a developing spiral, touching the axis. This motion was observed when the "resonance" condition $\omega_H = \frac{2\pi}{L} v_{||}$ was fulfilled. A phosphor-covered screen was placed at the magnetic field minimum. The amount of transverse energy in the beam electrons may be found by measuring the distance of the beam image on the screen from the trap axis and knowing the magnetic field strength in the screen region. Because of partial phase-defocusing, the beam image was produced on the screen in the form of a circumferential arc. A measuring grid was set up behind the screen with its own bias illumination, which made it possible to measure the distance of the beam from the axis with an accuracy of 0.002 m. It was established that at the moment of resonance the particles redistribute no less than 70% of the longitudinal energy into the transverse component.

Another method of determining beam transverse energy was also used. Beam transverse energy at the minimum magnetic field H_0 was found from the condition for reflection of charged particles from a magnetic "mirror": $\frac{W_{\perp 0}}{W_0} \geq \frac{H_0}{H_{refl}}$. By finding the beam reflection area and determining magnetic field strength

H_{refl}, we may readily ascertain the ratio of beam transverse energy to total energy η (in percentages): $\eta = \frac{W_{\perp 0}}{W_0} \cdot 100\% = \frac{H_0}{H_{refl}} \cdot 100\%$. The reflection plane proved to be diffuse; H_{refl} varied from 1.45 H_0 to 1.25 H_0; hence η = 69-80%.

A current collector with a small hole to let the electron beam pass into the trap, placed in front of the first mirror outside the trap, recorded the entry of most of the fast particle current at the instant of resonance capture. The phosphor layer applied to this collector made it possible to determine the region where the fast particles left the trap. It proved to be near the axis.

This indicated that the system, which at "resonance" very efficiently redistributes particle energy from the longitudinal into the transverse component, also redistributes particle energy from the transverse component into the longitudinal as well. This conclusion is confirmed by experiments to determine the number of charged particle reflections from the mirrors in the magnetic trap.

These experiments were conducted by two methods: In the pulse method, the modulator of the electron gun was fed a well-shaped rectangular pulse which blocked the current of electrons injected into the magnetic trap. At the moment of resonance capture of particles in the trap, the current pulse of fast electrons arriving at the electron collector (situated in front of the first mirror outside the trap) was obtained from this collector. From the current build-up time on the collector, the time the particles were held in the trap was determined, and -- from the geometry of the trap -- the number of charged particle reflections from the magnetic mirrors was found. These measurements gave a value of six for the number of reflections. The pulse method is not /415 accurate at low currents, since it must operate with low pulse amplitudes. An increase in electron injection currents in the trap above 10 microamp causes low-frequency oscillations in the trap.

To check the pulse-method results, the number of charged particle reflections from mirrors in the magnetic trap was found from the ratio of ion current in a probe (at the instant of resonance capture of particles in the trap) to ion current during a single passage of electrons past the ion probe. It was assumed that the ion current in the probe was proportional to the fast electron current. The collecting surface of the ion wall probe was large (about 0.6 m^2); this made it possible to work with small electron injection currents. The ions generated by ionization could drift freely across the magnetic field. Ion current in the probe during a single passage of the electron beam past the probe (the second mirror was cut out) was $I_1^+ \sim l$, where l is the length of the electron trajectory; the ion current in the probe under conditions of resonance capture of electrons in the magnetic trap was $I_T^+ \sim N_0 l$. The ion current ratio $\frac{I_T^+}{I_1^+} \approx \frac{N_0 l}{l} = N_0$ gives the number of electron reflections

from the magnetic mirrors. Error may occur in this method, because of the change in shape of the trajectories along which the electrons move under the various operating conditions in the trap, and because of supplementary ionization by slow secondary electrons. Calculations show that the error is no more than 35%. Measurement of the ratio of ion currents in the probe results in a value of 23 for the number of reflections.

The variation in input phase of the particles during their return trip through the segment of the spatially periodic magnetic field, as the result of magnetic field strengthening in the second mirror, did not perceptibly raise the number of reflections. Strengthening of the magnetic field in the first mirror resulted in an increased number of reflections, reaching saturation at $\frac{H_{mir}}{H_{0z}}I = 12$ and $\frac{H_{mir}}{H_{0z}}I = 3$. The maximum number of reflections was 53. The number of charged particle reflections from the magnetic mirrors did not appreciably vary with a change in pressure.

Our experiments have demonstrated that a magnetic field, whose resonance changes along the length of a trap, gives good redistribution of the longitudinal particle energy into the transverse component. The time that the electrons are held in a magnetic trap with a spatially periodic magnetic field whose resonance changes over the length of the trap is small, and is determined by an inverse process. The basic reason for the small hold time of charged particles in the trap is, in all probability, associated with the increased radial component of the magnetic field along the radius. At a distance of 0.035 m from the axis, where the charged particles enter the spatially periodic /416 magnetic field after reflection from the second mirror, the value of H_R is large, the "resonance" curve is sufficiently wide, and a reverse process may with great probability occur.

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